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Managing water resources from the energy - water nexus perspective under a changing climate: A case study of Jiangsu province, China

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ABSTRACT

As one of the most developed provinces in China, Jiangsu province is facing both energy and water stresses. The impact of energy production on water resource remains to be seen, especially in terms of a changing climate. In this study, we adopt a Long-range Energy Alternatives Planning System (LEAP) model combined with plant-level data to study the impact of energy policies on water resources management. The results indicate that energy efficiency improvements and industry structure optimization can result in 40% and 33% water withdrawal savings respectively in the future depending on the level of optimization. With several integrated measures, total water use can meet the 2030 targets set by the Jiangsu provincial government. Shifts in cooling technology can bring significant water-savings benefits and help fulfill water use-control targets. Furthermore, we find that the Suzhou and Xuzhou administrative areas will experience power output efficiency reductions and will need more water in 2030 under the RCP45 and RCP85 scenarios. More efforts are needed to mitigate climate change and offset its negative impact on energy and water resource. The results of this study will be informative for both resource management and policy design.

1. Background

The nexus between water and energy has attracted increasing attention over the past few years (Byers et al., 2014; Fang and Chen, 2016; Scott et al., 2011) because both resources are facing scarcity challenges, and more trade-offs between resource management are needed. The main purpose of this nexus study is to maximize human-environmental security by optimizing water and energy connections through different mechanisms (Dai et al., 2018; Mimoune et al., 2016). Water is required for coal mining, oil extraction, gas exploitation, electricity generation, biomass fuel irrigation, etc. (Dai et al., 2018; Feng et al., 2014; Mimoune et al., 2016). It is estimated that approximately 52 billion cubic meters of fresh water is consumed for global energy production annually. China ranked second for water consumption in electricity generation (Spang et al., 2014). At the same time, the nexus between water and energy also places pressure on energy production due to water resource restrictions in water-scarce areas in China (Yang et al., 2013; Zhang et al., 2017). Conflicts between water availability and energy sector demands have been identified in several studies (Qin et al., 2015; Xin et al., 2015; Zhang and Anadon, 2013). As China's total final energy demand and production are estimated to increase until 2030 (BP, 2017), the management stress in both resource areas will continue to rise, especially under the changing climate.

The water-energy nexus situation varies across China due to the uneven distribution of energy production and water resource availability, different management goals, and applicable technologies. Jiangsu province was chosen as a case for the nexus study at regional and city level in order to evaluate the impact of local management actions on water and energy resources for several reasons. China remained the largest consumer of energy resources around the world in 2016, with total energy consumption accounting for 23% of global energy consumption (BP, 2017). As one of the most developed regions in China, Jiangsu has witnessed increasing energy demand during the rapid industrialization and urbanization processes in China. Energy consumption in Jiangsu has increased 17% from 2010 to 2015 and ranked second nationwide in 2015 (National Statistical Bureau, 2016). In addition, its energy demand will continue to increase by 12% in 2020 compared to 2015 levels according to *The 13th Energy Five-Year Plan of Jiangsu Province* (People's Government of Jiangsu Province, 2017). According to the government's plan, both industrial and residential energy

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consumption structures will shift from predominantly traditional fossil-fuel energy to more alternative energy sources (Fan et al., 2017; Liu et al., 2016). At the same time, the energy sector remains to be the second-largest consumer of water resource in Jiangsu behind agriculture, exceeding 27% in 2015 (Water Resources Department of Jiangsu Province, 2016). In addition, Jiangsu is also facing significant challenges to achieve its water-use quantity control targets (as determined by the '3 Red Lines' regulation). Jiangsu used 57.74 billion tons of water in 2016, while its control target is 52.4 billion tons for 2020 and 60 billion tons for 2030 (Ministry of Water Resources of PRC, 2016).

2. Policies and regulations

Realizing the increasing importance of water resources management in adapting to energy demand, the past few years have seen an increase in efforts by China's central and local governments to address these issues. In 2012, the State Council demanded the implementation of the "strictest control over water resources" ('3 Red Lines') regulation, aiming to promote economic and social development adapting to total water resource constraints and aquatic environment carrying capacity (The State Council of PRC, 2012). In response to central requirements, the provincial government of Jiangsu also put forward a '3 Red Lines' regulation related to water resources exploitation and utilization control, water use efficiency control and pollution-limiting control in water function zones in the same year. The total water-use control target was also allocated to 13 cities in Jiangsu province (The Provincial Government of Jiangsu, 2012). Jiangsu has also implemented other policies to save water, such as increasing water prices.

During the past few years, Jiangsu has also launched several actions and policies to reduce air pollution and promote low carbon development which will have considerable impacts on the energy sector. For example, the Jiangsu provincial government launched the '263 action' in early 2017 to decrease total coal consumption, phase out unsustainable production capacities and optimize the power-generation structure (General Office of Jiangsu Provincial Government, 2017). Based on a series of actions, it remains to be seen whether the cumulative and interactive effects of these policies in the future will result in a meaningful alleviation of water and energy stresses in Jiangsu.

3. Literature review

Many attempts have been made to study water demand in the energy sector during past few years. An integrated hybrid life cycle assessment (LCA) model (combining LCA and input-output analysis (IOA) in general) has been used in many studies (Chang et al., 2015; Feng et al., 2014; Xin et al., 2015; Zhang and Anadon, 2013). The LCA model considers water use in all energy processes, including fuel acquisition, preparation, and device/plant construction and operation. Based on the physical evaluation of water demand during energy production, virtual water embodied in energy trading is also studied based on input–output analysis (IOA) (Duan and Chen, 2017; Zhu et al., 2015). Other studies employ the Regional Energy Deployment (ReEDS) model (Clemmer et al., 2013; Macknick et al., 2012b), Global Change Assessment Model (GCAM) (Davies et al., 2013; Talati et al., 2016) or integrated optimization models (Khan et al., 2017; Y. Zou et al., 2016) to evaluate this linkage. Parts of some studies focus on water use in single or multiple energy types, such as ethanol and petroleum gasoline (Wu et al., 2009) and coal and shale gas (Chang et al., 2015; Murray, 2013; Y. Zou et al., 2016). Many studies focus on water use in power generation from different perspectives, such as electricity capacity expansion (Davies et al., 2013), conventional and renewable electrical power plant comparisons (Fthenakis and Kim, 2010; Xin et al., 2015), and different power-generation technologies (Clemmer et al., 2013; Zhang et al., 2016b).

In terms of temporal scale, earlier studies of the water-energy nexus focused more on past calculations (Chang et al., 2015; Murray, 2013), while recent studies have focused more on predicting future situations (Feng et al., 2014; Qin et al., 2015; Talati et al., 2016) and emphasizing multi-objective management such as energy forecasting and planning with water constraints (Khan et al., 2017; Srinivasan et al., 2017), carbon emission constraints (Feng et al., 2014; Webster et al., 2013) or system cost minimization (Khan et al., 2016). In terms of spatial scale, there are a few global studies (Davies et al., 2013; Pfister et al., 2011); a considerable number of national studies involving the United States (Fthenakis and Kim, 2010; Li et al., 2011; Macknick et al., 2012b; Talati et al., 2016), Canada (Wu et al., 2009), Spain (Khan et al., 2016; Velázquez, 2006), India (Srinivasan et al., 2017) and China (Chang et al., 2015; Qin et al., 2015; Zhang and Anadon, 2013; Zhang et al., 2016b); some detailed studies are at the basin level (Clemmer et al., 2013; Y. Zou et al., 2016) or provincial and city level (Chang et al., 2015; Fang and Chen, 2016; Feng et al., 2014; Xin et al., 2015; Zhang and Anadon, 2013).

Previous studies show that the nexus between water and energy varies widely in different countries, regions and cities (DeNooyer et al., 2016) because resource endowments, management policies, and water demand of other sectors are unique to different regions. Furthermore, there is general agreement that local, high-quality data are requisite for water withdrawal and consumption factors that vary greatly across different regions and with different technologies (Macknick et al., 2012a; Qin et al., 2015). Hence, a regional study can provide more detail and precise information about the nexus of water and energy which might be concealed by larger scale studies. Based on the plant-level bottom-up approach combined with local management actions, the study can reveal unique conclusions about different regions and provide more practical information for resource management and policy design. In addition, a plant-level approach can combine with high-resolution climate scenarios to assess the impact of climate change. The general methodology used in this study could be applied to other regions and countries with sufficient data and clear resource management targets.

4. Methodology and data

4.1. Long-range energy alternatives planning system

Jointly developed by the Stockholm Environment Institute and Boston University, the LEAP model has been widely used to forecast energy supply and demand with different scenarios during the past years (Kachoee et al., 2018; Kumar, 2016; Kale and Pohekar, 2014). By combining a series of assumptions related to factors such as population, economic development, technology, and policy, the LEAP model can forecast the medium- and long-term energy supply and demand in a given region as well as its environmental impacts, including air pollution and greenhouse gas emissions. LEAP is a bottom-up econometric model based on an energy balance sheet. Each disturbance will make the production, processing, transformation and consumption parts form a new balance. By adjusting the demand side to predict the future situation of resource production, processing and transformation in a given region, LEAP can be used to simulate the impact of different policy decisions and technology choices on the future social and economic situation.

The LEAP-Jiangsu model is constructed in this study to forecast the future energy production and energy supply under a reference scenario and alternative scenarios, which contain energy demand, transformation and production modules. We divide the energy demand module into three industrial sectors and one household sector. The three industrial sectors are further divided into agriculture, industry, construction, transportation, commerce and other sectors, consistent with the scope of the statistical data. The household sector is also divided into urban and rural households, which represent the current household situation in Jiangsu. Considering the industrial sector, the terminal energy consumption of three industrial sectors is split into the product

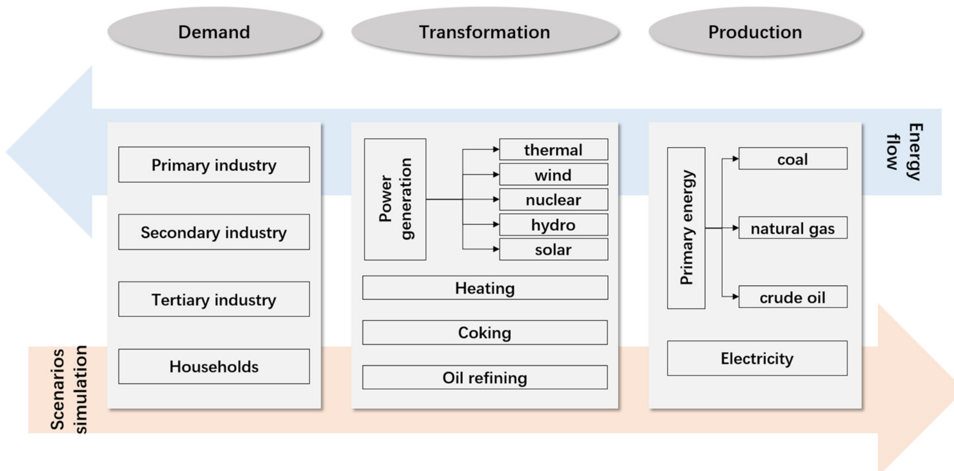


Fig. 1. Framework of LEAP-Jiangsu model.

of industrial added value and per added-value energy consumption. In addition, terminal energy consumption of the household sector is divided into urban and rural energy consumption. In the energy transformation module, we consider four processes: power generation, heating, coking, and oil refining, and the energy losses incurred in these processes. The electricity generation process consists of thermal power generation, hydropower generation, wind power generation, photovoltaic power generation and nuclear power generation. The production module includes primary and secondary energy resources. See Fig. 1.

4.2. Data sources and processing

In this model, the terminal energy consumption data for each economic sector, energy data for each transformation process and production data for each energy type are treated according to the *2015 Energy Balance Sheet of Jiangsu Province* (National Statistical Bureau, 2016). GDP, urbanization rate, urban and rural population data, industrial structure data and added-value data of the three industries are from the *Jiangsu Statistical Yearbook 2016* (Jiangsu Statistical Bureau, 2016). The power generation structure is based on the *China Electric Power Yearbook 2015* (Editorial Committee of China Power Yearbook, 2015). Based on the Jiangsu Energy Balance Sheet, we classify 27 energy types into 14 categories: raw coal, other coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, refinery gas, LPG, other oil, natural gas, heat and electricity. Gas making and natural gas liquefaction are not included because of their small input and output amounts, so we consider only electricity generation, heating, coking and oil refining as the four processes in the energy transformation module (see Table 1).

For the quantitative analysis of water demand, we focus on water withdrawal and consumption for the extraction of coal, natural gas and oil resources as well as water used for thermal power generation considering different cooling technologies and different installed capacities. Power generation data and water use data of each thermal power plant from the environmental statistics data of Jiangsu province and the water use parameters of different cooling technologies are used to calculate once-through and recirculating cooling technology proportion in order to choose different water-use parameters. Power plants included in the environmental statistics data of Jiangsu province are selected as main pollutant emitters instead of considering their water use. Therefore, power plants are not fully covered and water use information is not complete. To avoid large biases, we refer to the localized water consumption and withdrawal parameters provided by Zhang et al. (Zhang et al., 2016a). Table 2 provides the parameters of water consumption and withdrawal for coal mining, oil exploitation and thermal power generation. The water used in natural gas extraction is neglected for two reasons: local natural gas production in Jiangsu is

Table 1
Summary of data sources in this study.

Category	Data	Source
Base year data	Energy data	2015 Energy Balance Sheet of Jiangsu Province
		China Electric Power Yearbook 2015
	Social and economic data	Jiangsu Statistical Yearbook 2016
	Water use parameters	Zhang et al.
	Cooling technology proportion	Environmental statistics data of Jiangsu province
	Energy production proportion of 13 cities	Environmental statistics data of Jiangsu province
Scenario setting data	GDP growth rate	The 13th Five-Year Plan for National Economic and Social Development of Jiangsu Province
		The World in 2050: How will the Global Economic Order Change by 2050? (PwC)
	Urbanization rate	Urban System Planning of Jiangsu Province 2015–2030
		The 13th Five-Year Plan for Population Development of Jiangsu Province
	Electricity intensity	The 13th Five-Year Special Plan for Electricity Development of Jiangsu Province
		China Energy Outlook 2030
		The 13th Five-Year Plan for Energy Saving of Jiangsu Province
	Population growth rate	World Population Prospects (UNDESA)
	Industrial structure	China Energy Outlook 2030
	Clean energy structure	China Energy Outlook 2030
		The 13th Five-Year Special Plan for Electricity Development of Jiangsu Province
		Strategic Research on Energy Revolution of Production and Consumption
Climate data	Ambient air temperature	CORDEX database

Table 2
Parameters of water consumption and withdrawal for coal and oil production and thermal power generation.

Progress			Water withdrawal	Water consumption
Coal mining (m^3/ton coal)			1.68	–
Oil exploitation (m^3/ton oil)			0.22	–
Thermal power generation ($m^3/10^4$ KWh)	less than 100 MW	OT[a]	1031	5.56
		RC[b]	30.9	24.7
	100–300 MW	OT	1031	4.49
		RC	25.35	20.25
	300–600 MW	OT	1006	2.8
		RC	20.61	16.5
	600–1000 MW	OT	828	2.28
		RC	21.1	16.88
	more than 1000 MW	OT	828	2.28
		RC	21.1	16.88

Note:
[a] OT means once-through cooling.
[b] RC means recirculating cooling.

relatively small (National Statistical Bureau, 2016), and traditional natural gas extraction uses little water (Cai et al., 2014). Considering different cooling technologies used in power plants results in great differences in water withdrawals and consumption; water consumption in thermal power generation is also taken into account. By multiplying the amount of coal production, oil production and thermal power generation by corresponding water consumption and withdrawal parameters, water use of energy production can be obtained from 2015 to 2030. For future years, water use saving can be calculated by subtracting water use of REF scenario from water use of other scenarios.

Furthermore, projected energy production is allocated to 13 cities in Jiangsu to reveal the spatial distribution of water usage at a city level. The projected production of coal, natural gas and oil at the provincial level is allocated to each city according to its local energy production proportion in 2015 (National Statistical Bureau, 2016). Similarly, the projected power generation of Jiangsu is allocated to each city according to their local thermal power generation proportion of each power plant based on the environmental statistics data in 2016.

4.3. Scenario settings

In our study, we evaluate water demand for energy production in 2030 based on the LEAP model, using 2015 as the baseline year. To simulate the future energy production and power generation situation, four main scenarios are set up in our study: the reference (REF) scenario, energy efficiency (EE) scenario, industrial structure (IS) scenario and clean energy (CE) scenario. The key assumption parameters of these defined scenarios are shown in Table 3.

4.3.1. Reference (REF) scenario

Given the social and economic development requirements of Jiangsu province during the period of the 13th Five-Year Plan, it is assumed that the GDP of Jiangsu will increase at a rate of 7.5% during 2016–2020 (People's Government of Jiangsu Province, 2016a) and follow global economic growth (PwC, 2017) during 2021–2030. The urbanization rate is expected to reach 72% and 80% at the end of 2020 and 2030, respectively (Department of Housing and Urban-Rural Development of Jiangsu Province, 2015; People's Government of Jiangsu Province, 2016b). The electricity intensity data for urban and rural residents in 2020 and 2030 are from *The 13th Five-Year Special Plan for Electricity Development of Jiangsu Province* (Jiangsu Development and Reform Commission, 2016) and *China Energy Outlook 2030* (China Energy Research Society, 2016). National population growth is from the *World Population Prospects* (UNDESA, 2017), and the population

Table 3
Key assumption parameters for the LEAP-Jiangsu model in all scenarios.

Key assumptions	REF			EE		IS			CE		Cooling Structure	
									Low	High		
	2015	2020	2030	2016–2020	2021–2030	2015	2030	2015	2030	2030	2015	2030
GDP (billion RMB)	7012	10,066	17,698	–	–	–	–	–	–	–	–	–
Population (million)	79.76	81.33	82.28	–	–	–	–	–	–	–		
Urbanization Rate (%)	66.52	72.00	80.00	–	–	–	–	–	–	–	–	–
Industrial Structure (%)	6:45.7:48.3	5.5:44.5:49.8	5.2:43:51.8	–	–	6:45.7:48.3	4.5:30.5:65	–	–	–	–	–
Urban and Rural Energy Intensity (coal equivalent/ capita)	0.20:0.18	0.39	0.60	–	–	–	–	–	–	–	–	–
Industry Energy Intensity Annual Change (%)	–	–	–	−3.50	−2.00	–	–	–	–	–	–	
Commerce and Service Energy Intensity Annual Change (%)	–	–	–	−1.50	−1.00	–	–	–	–	–	–	–
Power Generation Structure (thermal: hydropower: wind: solar: nuclear) (%)	–	–	–	–	–	–	–	94:0.27:1.34:0.44:3.76	76:2:10:8:4	68:3:13:10:6	–	–
Cooling Structure (once-through: recirculating: sea water) (%)	–	–	–	–	–	–	–	–	–	–	51.2:44.6:4.2	47.2:48.6:4.2

proportion of Jiangsu is assumed to remain the same. Under the REF scenario, IS changes and energy import and export amounts will follow past trends. Notably, the REF scenario does not consider any other policies or measures that aim to strengthen energy conservation and reduce emissions.

4.3.2. Energy efficiency (EE) scenario

The EE scenario adds energy efficiency improvements based on the REF scenario. According to *The 13th Five-Year Plan for Energy Saving of Jiangsu Province*, the energy intensity of the industrial sectors is expected to decrease by 18% in 2020 (Jiangsu Economic and Information Technology Commission, 2016). Therefore, it is likely that a series of economic and energy policies will be implemented in the near future. Thus, we set an annual decrease in the industrial energy intensity rate of 2.0–3.5%, together with a deceasing rate of 1.0–1.5% for the commerce and service industries during the period of 2016–2030. Other parameter settings are the same as those in the REF scenario.

4.3.3. Industrial structure (IS) scenario

Jiangsu province has implemented great efforts to optimize its industrial structure since 2015. It is highly probable that the industrial structure of Jiangsu will be optimized in the future. To simulate the pathways of industrial structure optimization, we construct the IS scenario based on the REF scenario. On March 1st, 2016, the China Energy Research Society released *China Energy Outlook 2030*. The report takes 2014 as the base year, 2020 as the node year and 2030 as the outlook year. It provides a comprehensive outlook on China's energy production, consumption, trade, infrastructure construction and market supply and demand trends. In Chapter One, ‘Economic and social development outlook’, the report mentions that after 2020, China will enter the stage of post-industrialization development. The proportion of secondary industries in 2020 and 2030 will be 37.6% and 30.5% respectively, and the proportion of tertiary industries will be 54.7% and 65% respectively. Economic growth will shift from a rapid, investment-driven nature to a more stable consumption-driven model. Miniaturization, intellectualization and specialization of production will become a new feature of secondary industry organization. So the industrial structure of Jiangsu is set as 4.5:30.5:65 in 2030 rather than 6:45.7:48.3 in 2015 based on the *China Energy Outlook 2030* (China Energy Research Society, 2016). Other parameter settings are the same as those in the REF scenario.

4.3.4. Clean energy (CE) scenario

When compared to clean energy power generation, conventional thermal power generation releases more human-induced greenhouse gas emissions (Zubelzu and Álvarez, 2016) and air pollutants as particulate matter (PM_{10}) and sulfur dioxide (SO_2) that pose substantial threats to natural ecosystems and human health (Thanh and Lefevre, 2001). Accordingly, national and provincial governments have increasingly been encouraging clean energy power generation in recent years, including nuclear power and renewable energy power. In the next few years, Jiangsu is expected to continuously promote the expansion of clean energy power generation (Jiangsu Development and Reform Commission, 2016; People's Government of Jiangsu Province, 2017). Thus, a clean energy scenario is constructed in our study. We set low and high rates of clean energy development, including hydropower generation, wind power generation, solar power generation and nuclear generation based on national and provincial regulations (China Energy Research Society, 2016; Jiangsu Development and Reform Commission, 2016; National Development and Reform Commission, 2016).

The integrated scenarios are developed based on the EE scenario, IS scenario and CE scenario to test the impacts of combined action. Apart from the different development scenarios, a transformation in cooling technology is also considered in our study. Once-through cooling technology that involves higher water withdrawals has been adopted in about half of the power plants in Jiangsu. Other power plants have adopted recirculating cooling technology, while a smaller proportion of power plants have adopted seawater cooling technology. Through the repeated use of cooling water, recirculating cooling greatly reduces water withdrawal compared with once-through cooling and is now being popularized nationwide. To reflect the different technology options for power plants, a gradual change in cooling technology structure is defined first in all scenarios. Further, we discuss the effects of cooling technology structure changes on total water use.

Climate change will lead to an increase in water supply and demand discrepancies (Bartos and Chester, 2015; Strzepek et al., 2016). Many studies have found that global or regional power generation is vulnerable to climate change due to its large water withdrawals (Behrens et al., 2017; Mouratiadou et al., 2016; Teotónio et al., 2017; Vliet et al., 2016; Zheng et al., 2016). High temperatures can cause efficiency losses in the cooling process during power generation. In general, a rise of 1 °C in ambient cooling water temperature could cause a drop in power output of 0.12–0.45% (Henry and Pratson, 2017). To study the impacts of climate change on power generation, we roughly calculate power output and related water demand changes in 2030 under two different climate change mitigation scenarios: RCP45 and RCP85. The predicted ambient temperature of 13 cities in Jiangsu under different scenarios is based on climate data extracted from the Coordinated Regional Climate Downscaling Experiment (CORDEX) database, which provides regional climate downscaling projections (Giorgi and Gutowski, 2015; L. Zou et al., 2016). We use MATLAB and GIS to analyze the data. A fitting equation is used to convert ambient air temperature to water temperature (Tian, 2014). For a rough evaluation, the efficiency of thermoelectric plants is assumed to decline by 0.325% for each 1 °C of warming.

$$y = 22.4811 - \frac{10.2389}{1 + e^{(x-18.4752)/1.8556}} \tag{1}$$

Where y refers to water temperature and x is ambient air temperature.

5. Results and discussion

5.1. Energy production at provincial and city levels

Jiangsu province has relatively scarce natural resource reserves. Limited by the shortage of local oil resources and natural gas resources, high energy demands in Jiangsu are mainly met by imports from other provinces or countries. In 2015, local coal, natural gas, oil and thermal power production in Jiangsu was at 19,189 thousand tons, 37 million cubic meters, 1905 thousand tons and 405 billion KWh, respectively. 87% of the demand for coal is met by imports, as well as 99% of the demand for natural gas and 97% of the demand for oil. In 2030, local energy production in Jiangsu will increase to a certain extent, but the strong dependence on energy imports will not change. In comparison to the REF scenario, there is a significant decline in local coal, oil and thermal power production in the EE scenario, while oil production experiences an increase in the IS scenario, mainly because of high oil consumption in the tertiary industry. Fig. 2 presents the future production of three energy types and thermal power generation in 13 cities in Jiangsu. Because of limited local natural gas production, natural gas production can scarcely be seen in the histogram. The diagram shows that Suzhou and Xuzhou are the top two cities in terms of local energy production, while Lianyungang ranks last. Benefiting from its leading role in China's export-oriented economy, Suzhou has enjoyed rapid economic development for decades. Due to many industrial enterprises, Suzhou consumes a large amount of electricity. In comparison with other cities, Lianyungang's economic base and infrastructure are obviously lagging. Coal and thermal power still account for a large proportion of energy production. The reduction in coal production in the EE scenario is much greater than that in the IS scenario because of the improvements in energy efficiency in both the secondary and tertiary

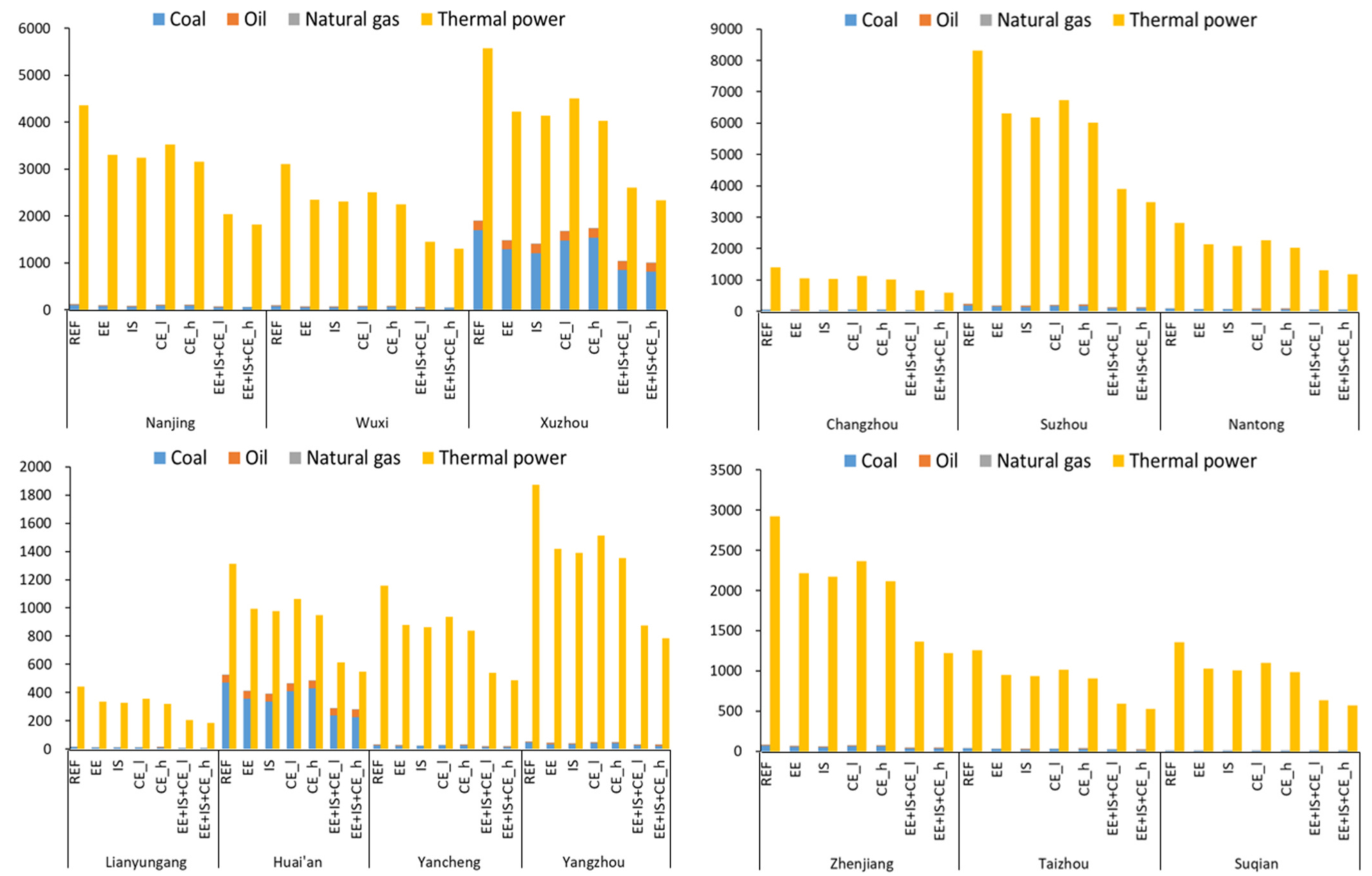


Fig. 2. Coal, oil and natural gas production and thermal power generation across scenarios in 13 cities in Jiangsu province in 2030 (10^4 t of equivalent coal).

industries. Moreover, promoting clean energy power generation plays an important role in traditional energy savings, which may further mitigate climate change and reduce air pollutant emissions.

5.2. Water used for energy production at provincial and city levels

Current water use in energy production across the 13 cities is shown in Fig. 3. To reflect the spatial differences in water stress, per capita water resources of the 13 cities are considered. According to internationally accepted standards of water scarcity, per capita water resources below 3000 m^3 are considered mild shortages of water, below 2000 m^3 are considered a moderate shortage of water, less than 1000 m^3 are considered a serious shortage of water, and under 500 m^3 are considered a severe shortage of water. As a severely water-scarce city, Xuzhou has the second-highest water use volume, mainly due to its large-scale coal mining operations. Suzhou has the largest energy production-related water use due to its position as the highest thermal power generator in Jiangsu. In addition, in comparison to coal, oil and natural gas production, thermal power generation is the largest user of water and is responsible for over 99% of total water withdrawals.

Significant increases in energy production in the future will inevitably have a large impact on water resources. Fig. 4 summarizes future water demand for energy production under different scenarios at a provincial level. Under most scenarios, water demand continues to increase after 2015, while decreases in water demand can be seen in several integrated scenarios. Under the REF scenario, water withdrawals and consumption are almost 42.3 billion m^3 and 1.2 billion m^3 respectively in 2030, double the 2015 values. The EE scenario resulted in a 40% savings in water withdrawals and a 33% savings in water consumption in comparison to the REF scenario, while the IS scenario resulted in a 33% savings in water withdrawals and a 20% savings in water consumption. Furthermore, an additional 6.2% water savings is provided by the rapid pace of clean energy development.

At the city level, the water withdrawal savings in energy production in the 13 cities compared to those in the REF scenario are presented in Fig. 5. To reflect the difference in total water use, the proportion of water used for energy production to total planned water use in each city is shown in the base map. The 2030 total planned water use data are derived from the *Water Pollution Prevention and Control Program* and *Implementing Opinions on Implementing the Strictest Water Resources Management System* at the city level. The optimization of industrial structure contributes more to water withdrawal savings than energy efficiency improvements. When compared to a single control, integrated scenarios show greater potential for water withdrawal savings. Xuzhou, Suzhou and Nanjing rank as the top three cities in terms of water withdrawal savings potential, mainly due to their large energy production bases. Considering the restrictions of total water use, Xuzhou and Zhenjiang have the two highest proportions of water use for energy production, which may result in extra pressure on water use in other sectors.

5.3. Water use in compliance with the '3 Red Lines'

According to the '3 Red Lines' regulation for Jiangsu province, total provincial water use should be kept within 58 billion m^3 by 2020 and 60 billion m^3 by 2030. To determine whether these targets can be met, the total water use of households, agriculture, industry and ecology is taken into account. Total water use is identified as the water withdrawn. The provincial agriculture water use data for 2030 is derived from the *Water-saving plan for agricultural irrigation of Jiangsu Province*, and the data for 2020 is calculated through a linear interpolation method. For households, we refer to other studies that demonstrate assumed future household water use is a function of population and per capita GDP (Bijl et al., 2016). Then, the municipal regional factor is

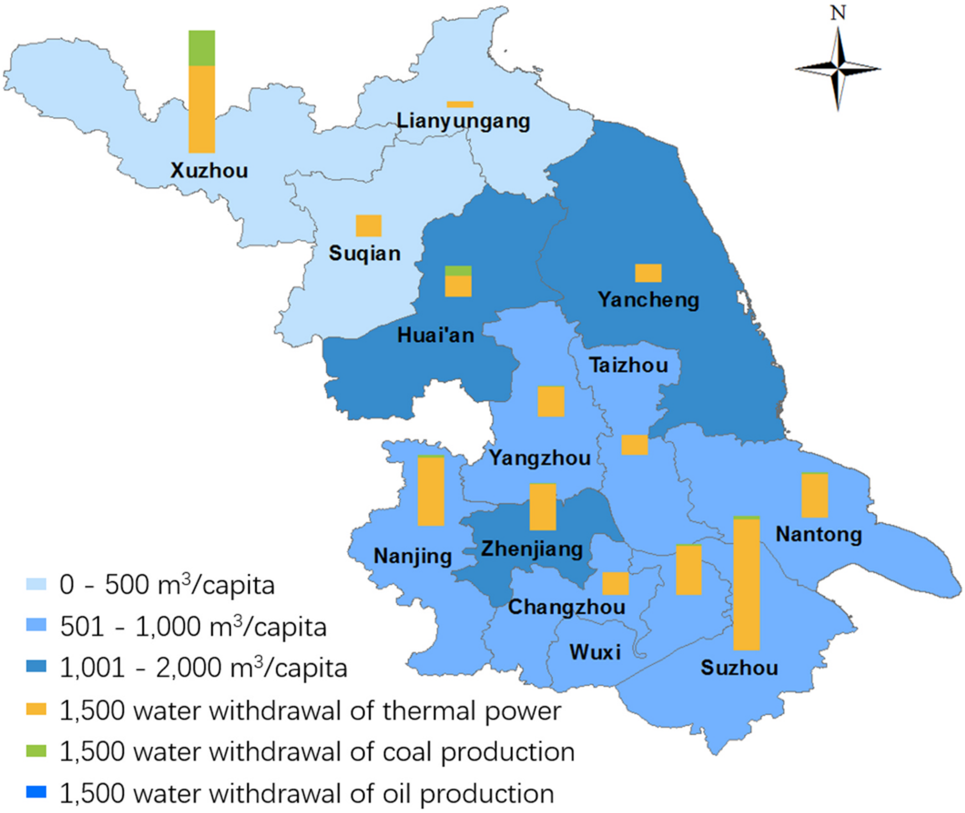


Fig. 3. Water stress and water withdrawal for energy production in 13 cities in Jiangsu province in 2015 (10^4 m^3). Note: the dark and light blue on the base map represents the per capita water resource levels of the 13 cities according to standards of water scarcity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

modified from 0.58 to 0.49 using the actual data for provincial household water use in 2015 (Ministry of Water Resources of PRC, 2016). In addition, we assume that the proportion of energy production water withdrawals to industrial water use will remain the same until 2030. In addition, ecological water use remains the same as it is a nearly-negligible proportion of water use. As seen in Fig. 6a, the 2020 target cannot be met in either scenario, and the 2030 target can be met only under the last two integrated scenarios. Agriculture and industry are the top two sectors in terms of water use in the future. Industrial water use will decline with more control measures, and more measures are needed to decrease agricultural water use.

To reflect the separate impacts of cooling technology structure changes on total water use, a comparative study is conducted that considers once-through cooling technology accounting for both 40% and 30% of the water use in 2030. Compared to once-through cooling technology, water resources can be recycled continuously in recirculating cooling technology, and effluent is also reduced substantially. Currently, recirculating cooling technology has become the most widely popularized type of cooling technology. Because of the lower water withdrawal intensity of the recirculating cooling technology, optimization of the cooling technology structure greatly reduces water use in power generation.

As shown in Fig. 6b and c, water savings for total water use under the REF scenario are 7.31 and 17.46 billion m^3 respectively for the 40% and 30% deployment of once-through cooling technology in 2030 in Jiangsu. When lower once-through cooling technology is considered, more water is saved. When once-through cooling technology accounts for 40% of the water use in 2030, total water use shows an obvious decrease in all scenarios, and the integrated scenario can meet the 2030 target. When once-through cooling technology accounts for 30% of the water use, a further decrease appears in all scenarios, and only the first five scenarios fail to meet the 2030 target. However, all scenarios fail to meet the 2020 target whether the cooling structure change is considered or not. We can see that current policies on energy saving and energy structure change do have a positive impact on water-resource management policy. However, joint implementation of multiple

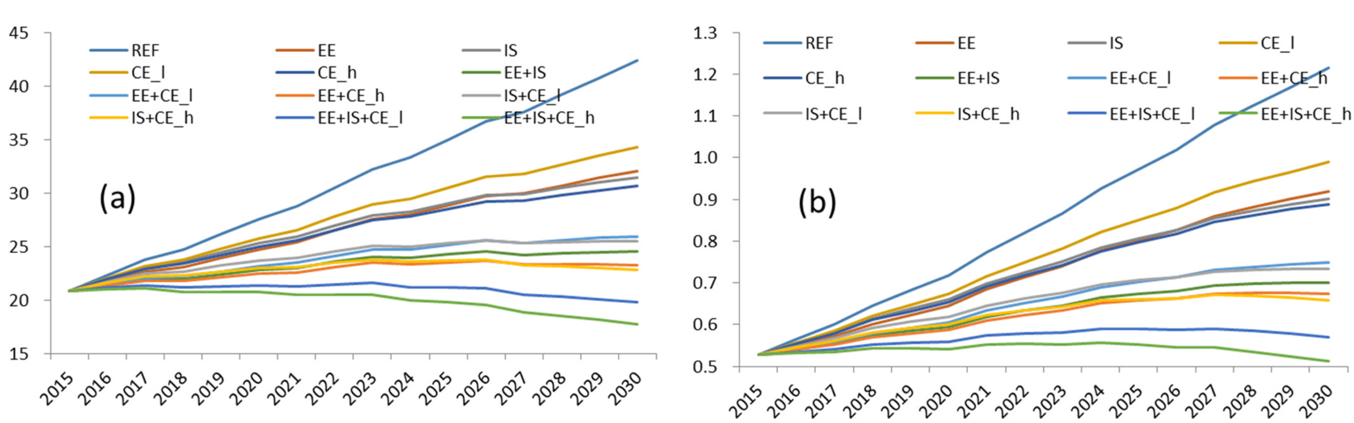


Fig. 4. Water withdrawal (a) and water consumption (b) of energy production across scenarios in Jiangsu province during 2015–2030 (billion m^3).

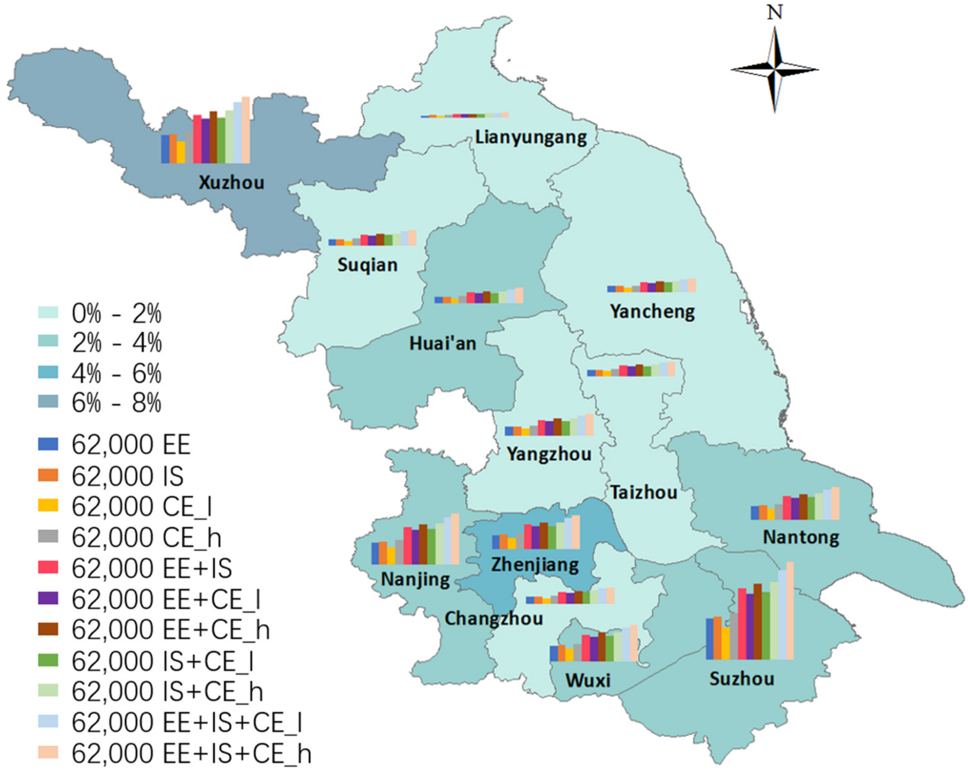


Fig. 5. Water withdrawal savings in energy production compared to savings in the REF scenario in 13 cities in Jiangsu province in 2030 (billion m^3). Note: the dark and light green on the base map represents the proportion of water used for energy production to total planned water use in each city in 2030.

policies can have a synergistic reaction.

5.4. Effects of climate change on power generation

Power generation systems in most cities will be influenced by higher ambient water temperatures, so the effects of climate change on power generation are considered. Power output influence and water demand changes in the REF scenario in 2030 under the two RCP scenarios are presented in Fig. 7. This figure shows that the annual average temperature in 2030 is higher than that in 2015 under both the RCP45 and RCP85 scenarios, while the increase is larger in the RCP85 scenario than in RCP45. At a month level, July and September have much larger temperature increases than other months under both scenarios. At a regional level, cities in the south of Jiangsu will experience fewer temperature increases than will northern cities. Fig. 7 illustrates that all cities will use more water due to power output reductions resulting from ambient water temperature increases. Suzhou, Xuzhou and Nanjing are the cities most influenced due to their energy structures and temperature increases. Changzhou and Lianyungang are less impacted than other cities. Overall, we find that climate change will put more stress on local energy production and related water resource management. Hence, more efforts are needed to mitigate climate change to reduce its impact on energy production, and stronger actions, such as energy efficiency improvements and industrial structure optimization, are needed to offset the negative impact of climate change on water resources.

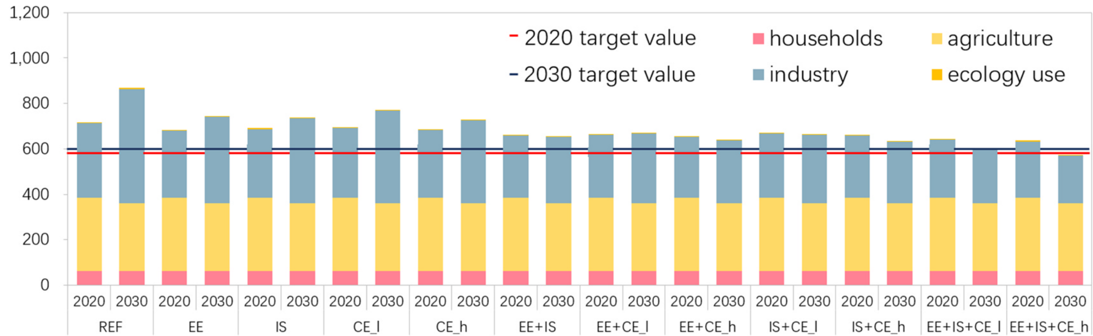
5.5. Comparison with other studies

Water use parameters are the most important factors affecting the results. To verify the reliability of the results, several former studies conducted in China related to water demand for energy production are also collected. The relative water use parameters in these studies are categorized in Table 4. Using these parameters, the water demand for energy production in Jiangsu in the future is recalculated and shown in Fig. 8. We find that our results are comparable in terms of the order of magnitude and can reflect the nexus between energy and water in Jiangsu and its 13 major cities.

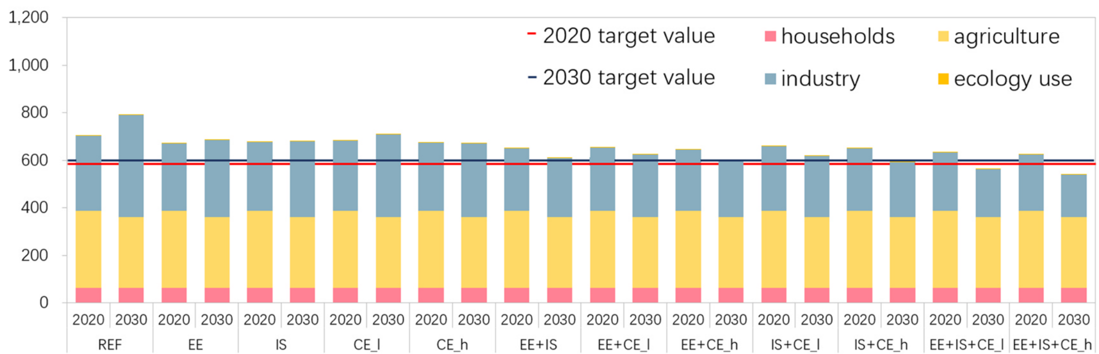
This study also has some limitations. Water use for coal mining, oil exploitation and thermal power generation is used in our study, and other water uses are excluded. In addition, the coal, natural gas and oil production in the 13 cities is obtained by distributing the total energy production in Jiangsu due to lack of data. Future research can refine the power generation mode, select more accurate local water use parameters and consider LCA to predict the future energy and water nexus dynamic at provincial or city levels.

6. Conclusions and policy Implications

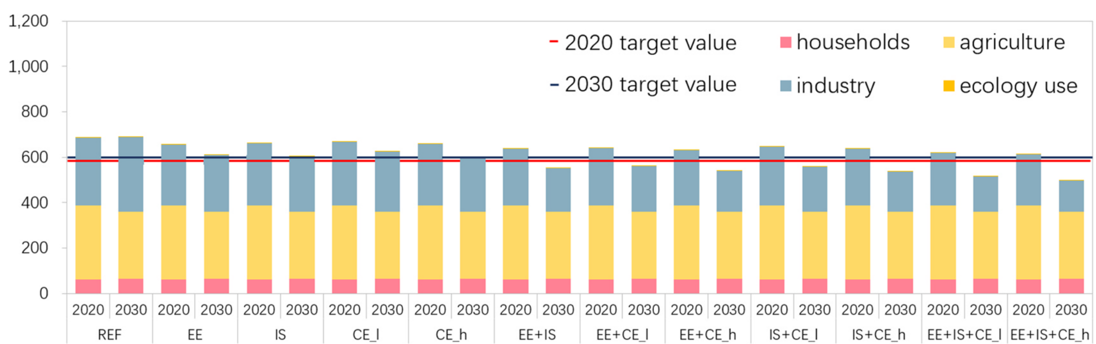
This study calculated water withdrawals and water consumption for energy production under different energy management scenarios in Jiangsu province from 2015 to 2030. With the growth of energy demand in Jiangsu province in the future, water use for energy production will also increase correspondingly. If control measures are taken to decrease the energy intensity of the production process in order to promote industrial structure optimization as well as clean energy development, a large amount of water resources will be saved when compared to current trends. Water-saving effects will be more notable for Xuzhou, which is a large coal producer, and Suzhou and Nanjing, which are large producers of energy. We can see that current policies on energy saving and energy structure change do have positive impact on water management policy. However, joint implementation of multiple policies can have synergistic reaction. So co-benefit of water savings needs to be considered when local governments make management decisions. When formulating policies and laws on energy production, transportation and consumption, governments should fully consider its impact on water resources and coordinates them with the water resources management target in China. On one hand, energy policies and



(a)



(b) Once-through cooling technology accounts for 40% in 2030



(c) Once-through cooling technology accounts for 30% in 2030

Fig. 6. Total water use in Jiangsu province in 2020 and 2030 considering different cooling structure changes (10^8 m^3).

development plans should be formulated according to local energy and water-resource conditions. On the other hand, in terms of clean energy policies, governments should fully assess the impact of clean energy production on water resources.

At the same time, water withdrawals will be greatly reduced as recirculating cooling technology is popularized, which will also help to alleviate the impacts of thermal effluent into river ecosystems and environments (Logan and Stillwell, 2018). However, thermal pollution from energy has not been paid enough attention in China, even though the Yangtze River is already among the most thermally-impacted watersheds globally, and thermal power plants along with the river are the main heat emitters (Raptis et al., 2017). Cost is one of the main reasons that plants refrain from choosing recirculating cooling technology. Therefore, cooling technology management should be more carefully considered for its environmental benefits and economic costs. The government should assess the challenges of cooling technology transformation in power plants according to local conditions, formulate reasonable and targeted technical transformation plans, and provide tax incentives or other policy support for power plants who actively change cooling technology.

Moreover, implementing control measures will effectively reduce the proportion of energy production-related water use in terms of the total amount of water constraints, which will contribute to alleviating the conflict between agricultural, household and energy sector water use, and promote the realization of the '3 Red Lines' for water resource management in Jiangsu province. As this study has shown, more efforts are needed to offset the impact of climate change on both energy and water resources for sustainable resources management.

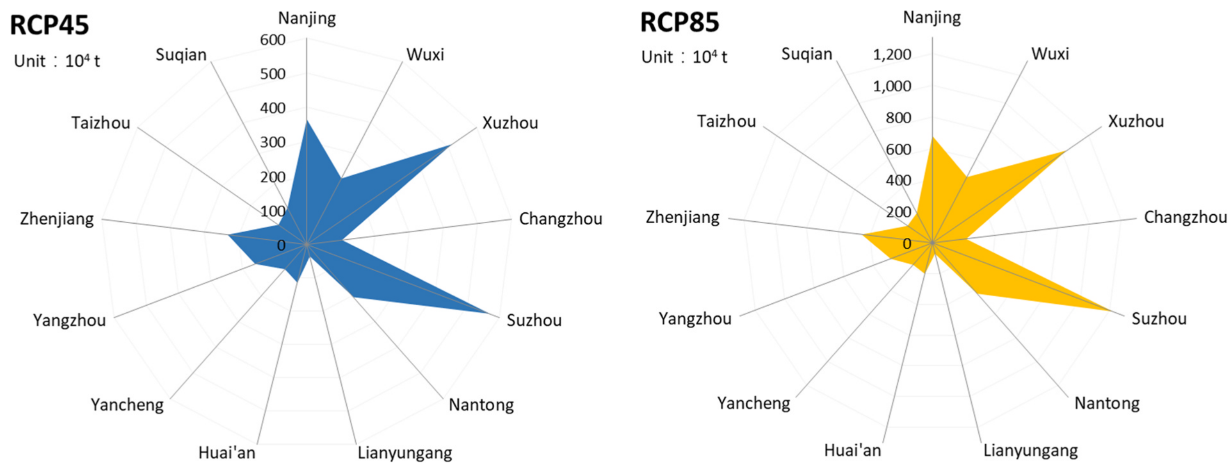


Fig. 7. The effects of climate change on water resources in the 13 cities in the REF scenario under the RCP45 and RCP85 scenarios in 2030.

Table 4
Comparison of parameters of water consumption and withdrawals with results in the literature.

Parameters	This study	Zhang et al. (2016b)	Cai et al. (2014)	Chang et al. (2015)
Coal mining (m^3/ton coal)	1.68	NG	1.50	0.62
Oil exploitation (m^3/ton oil)	0.22	NG	0.22	NG
Thermal power generation using once-through cooling water withdrawal ($m^3/10^4$ KWh)	82.8–103.1	NG	132	NG
Thermal power generation using once-through cooling water consumption ($m^3/10^4$ KWh)	2.28–5.56	0.79	NG	2.34
Thermal power generation using recirculating cooling water withdrawal ($m^3/10^4$ KWh)	2.06–3.09	3.20	NG	NG
Thermal power generation using recirculating cooling water consumption ($m^3/10^4$ KWh)	1.65–2.47	2.13	NG	2.34
Region	Jiangsu	China	China	China
Year	2015	2012	2010	2007

Note: NG means not given in the literature.

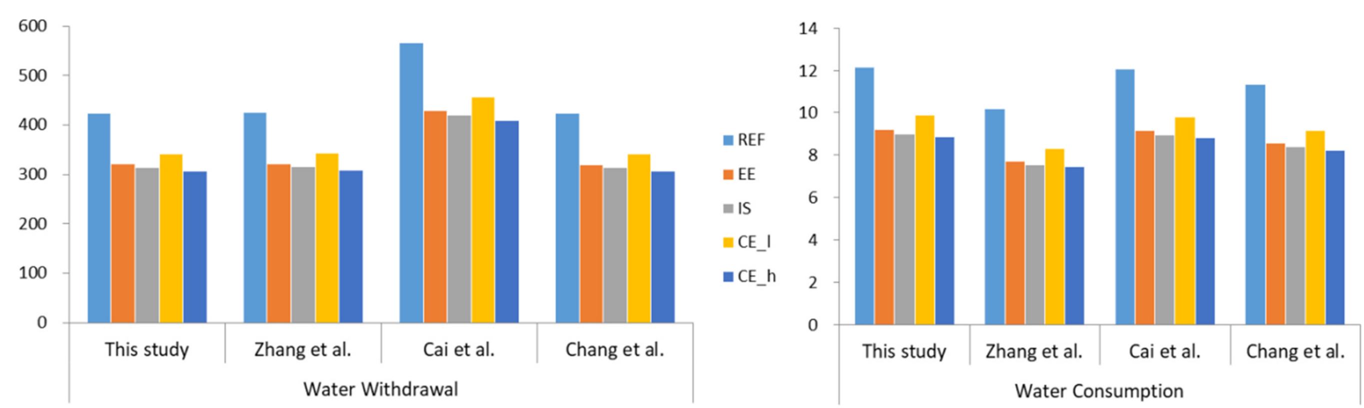


Fig. 8. Water withdrawals and water consumption in energy production across scenarios in Jiangsu province in 2030 using parameters in the literature (10^8 m^3).

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